PL-TR-94-2246

WHAT SUPPORTS THE WEIGHT OF THE IONOSPHERE

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5 October 1992

Scientific Report No. 2

PHILLIPS LABORATORY
Directorate of Geophysics
AIR FORCE MATERIEL COMMAND
HANSCOM AIR FORCE BASE, MA 01731-3010

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	5 October 1992	Scientific No. 2

4. TITLE AND SUBTITLE
What Supports the Weight of the Ionosphere

5. FUNDING NUMBERS
PE 61102F
PR 2310 TA GL WU AA

F19628-93-K-0008

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Phillips Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

Contract Manager: David Anderson/GPIM

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
PL-TR-94-2246

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) This paper discusses the various physical processes which support the weight of the ionosphere. First, the investigation discusses the situation at the magnetic equator where the geomagnetic field is horizontal and then later discusses the mid-latitude region. It is found that at the magnetic equator, the different velocities of the ions and electrons creates a polarization current and subsequent electric field. When collisions are added, this provides a drag on the upward motion of the plasma and this is balanced by a change in the eastward electric field. When the geomagnetic field is not horizontal, viscous interaction with the neutral atmosphere generates currents and electric fields to counter-balance the gravitational force.

14. SUBJECT TERMS
Ionosphere
Gravity
Electric fields
Kinetic energy

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

WHAT SUPPORTS THE WEIGHT OF THE IONOSPHERE

October 5, 1992

In the absence of a geomagnetic field, the answer is simple. The weight is borne by the neutral atmosphere due to the viscous interaction associated with the downward diffusion of plasma. The actuality for Earth is that the geomagnetic field bears some of the weight – practically all of it at the geomagnetic equator. We will discuss first the situation that prevails at the geomagnetic equator where the magnetic field is horizontal, and later discuss the situation where the magnetic dip angle is different from zero.

Consider first a plasma whose density is constant with height, with no horizontal electric field. The presence of a gravitational field causes a gravitationally induced electric current to flow. Consider the particles to be initially at rest when the gravitational field is turned on. The ions and electrons start to fall but are quickly turned aside by the magnetic field; the ions follow cycloidal paths to the east and the electrons smaller amplitude cycloidal paths to the west. The resulting eastward current supports the plasma against gravity, and the magnetic field bears the weight of the plasma. One might suppose that the ions, because of their greater mass and the greater radii of curvature of their motions, carry most of the gravitationally induced current, but this is not so. The charge separation associated with the different amplitude cycloids cause a vertical electric field to develop that supports most of the weight of the ions and pulls downward on the electrons, essentially transferring the weight of the ions to them.

The orders of magnitude involved are as follows for $B = 3 \times 10^{-5}$ tesla and ion mass 30. For ions and electrons, the gyro frequencies are 5.27×10^6 and 96 radians/s; the thermal velocities are 1.3×10^5 and 560 m/s and the gyro radii are 0.024 and 5.8 m for kT = 0.05 eV. These quantities are not needed in the following analysis, but they are useful in developing a sense of perspective. The numerical values presented below are amazing; are they believable? Neglecting for the moment the charge-separation interaction between ions and electrons, the drift velocity of an ion in a horizontal magnetic field would be $v = mg / Be \approx 0.1$ m/s. The vertical descent Δh of an ion in the gravitational field required to produce this velocity is given by $mg\Delta h = mv^2$; thus $\Delta h = v^2 / g \approx 1 \times 10^{-3}$ m. (At 200 km, g = 9.5 ms^{-2}). This would produce a polarization charge density $ne\Delta h$ and an upward directed electric field $ne\Delta h / \varepsilon_o \approx 1.86$ V/m for $n = 10^5$ ions cm^{-3}. The upward electrical force on the ions would be a factor of about 6.27×10^5 larger than the gravitational force, the electrical force being $eE \approx 2.98 \times 10^{-19}$ N and the gravitational force $mg \approx 4.8 \times 10^{-25}$ N. A charge separation field must develop to prevent this from happening.

Because of the great disparity between the electrical and gravitational forces mentioned above, the charge separation field requires that electrons bear almost the total weight of the ions, and this in turn requires that the charge separation field be given by $E = m_i g / e$. For the values assumed here, ion mass 30, the electric field has the value 3.13×10^{-6} V/m. This establishes the magnitude of the charge separation:

$$\Delta h_i - \Delta h_e = \varepsilon_o E / ne = \varepsilon_o m_i g / ne^2 = g / \omega_{pi}^2 ,$$

where Δh_i and Δh_e are the downward displacements of the ions and electrons and $\omega_{pi} = \sqrt{ne^2 / m_i \varepsilon_o} \approx 7.6 \times 10^4$ r/s is the ion plasma frequency. The difference between the ion and electron downward displacements in the present context is 1.64×10^{-9} m.

The electron drift velocity can be obtained from the requirement that the electrons carry a current sufficient to support the weight of the ions, i.e., $ev_e B = m_i g$, or $v_e = m_i g / eB = g / \omega_{gi}$, where v_e is the electron drift velocity and ω_{gi} is the ion gyro frequency. Thus the electron drift velocity has the value 0.1 m/s The electrons must move a distance Δh_e in the vertical electric field to gain the kinetic energy associated with their drift velocity, where $\Delta h_e Ee = m_e v_e^2$; thus Δh_e has the value 1.88×10^{-8} m, very small compared to the electron gyro radius. As $\Delta h_i - \Delta h_e$ has the value 1.64×10^{-9} m, Δh_i is larger than Δh_e by the factor 1.09. The ion drift velocity is $v_i = \omega_i \Delta h_i = 1.96 \times 10^{-6}$ m/s, smaller than v_e by the factor 2×10^{-5}. The current carried by the ions is smaller than that carried by the electrons by this same factor, and this also represents the fraction of the weight of the ions that is borne directly by the magnetic field rather than being transferred first to the electrons.

Application of gravity to the ions without taking the interaction with electrons into account would, as mentioned earlier, produce a surface charge density $ne\Delta h = \chi_e \varepsilon_o mg / e$, where $\chi_e = nm / eB^2$ is the electrical susceptibility. The electrons act like the polarization charges in a dielectric and produce a compensating surface charge density $(\chi_e - 1)\varepsilon_o mg / e$, leaving a net surface charge density $\varepsilon_o m_i g / e$ that produces electric field $E = m_i g / e$.

Because of the smallness of the net force on the ions $(m_i g - Ee)$, ion collisions are not of much significance; they might slightly increase the magnitude of the electric field and stop the eastward drift of ions completely. Electron collisions, on the other hand, are of primary importance. They are also more frequent than ion collisions, generally by two orders of magnitude or more. When the electron collision frequency becomes comparable to the electron gyro frequency, the weight of the plasma is transferred to the neutral atmosphere rather than to the magnetic field

Next consider the effects of pressure gradients in the plasma when the density distribution is not constant with height. Then there is a magnetization current. Magnetization current is also present in the case of constant density, but then there is no net current inside the plasma, there being complete cancellation at the boundaries between adjacent volume elements. There is net magnetization current only around the plasma boundaries in such a sense as to reduce the magnetic field in the region occupied by the plasma and to confine the plasma. In the non-uniform density case, there is net magnetization current within the body of the plasma in such a sense as to flow around the region of highest density and reduce the magnetic field strength in that region. Above the ionospheric maximum, the magnetization current is oppositely directed to the gravitationally induced current. If the ion distribution is hydrostatic, the two cancel and there is no net current and none of the weight of the plasma is borne locally by the magnetic field; it is supported instead by its own pressure distribution. As one approaches the ionospheric peak from above, progressively more of the weight of the plasma is supported by the magnetic field, starting where the ion distribution first departs from hydrostatic. At the ionization peak, the weight of the plasma at the peak is borne by the magnetic field, but much of the weight of the overlying plasma is not; it is supported instead by the plasma pressure at the peak.

Below the ionization peak, the magnetization current and the gravitationally induced current are in the same direction, eastward. At each altitude below the ionization peak, the gravitationally induced current transfers the weight of the plasma at that altitude to the magnetic field, while the magnetization current transfers part of the plasma pressure to the magnetic field. Where the plasma pressure has fallen to a low value below the F2 peak, virtually all of the weight of the overlying ionosphere has been transferred to the magnetic field. In this way, all of the weight of the ionosphere above the ionization peak that is not transferred in situ to the magnetic field is transferred to the magnetic field by magnetization currents near the ionization peak.

The magnetization current is carried equally by electrons and ions when collisions are negligible. If the electron and ion temperatures are not equal, charge separation effects must act to keep the currents equal. If collisions interfere with the current carried by one component, then charge separation acts to shift current to the other component.

What are the effects of an imposed eastward electric field and Pederson conductivity? An eastward field causes an upward plasma drift E/B. In the absence of collisions, the plasma acts like a perfect dielectric in which the stored energy density available as electric field energy is just the kinetic energy density of the upward plasma drift, $\rho v^2/2 = \rho E^2/2B^2 = (\rho/\varepsilon_o B^2)\varepsilon_o E^2/2$; i.e., the electrical susceptibility is $\chi_e = \rho/\varepsilon_o B^2 \approx 6\times 10^5$ for $n = 10^5$ ions/cm³ and B = 0.3 gauss. The kinetic energy is produced as a result of the polarization of the plasma under action of the applied electric field, the ions and electrons each moving a gyro radius in opposite directions.

Electrical energy is expended in producing the kinetic energy; once produced, no additional energy input is involved in maintaining the kinetic energy in the absence of collisions. However, the imposition of an eastward field violates one of the conditions that was applied in discussing the gravitationally induced current - that there be no horizontal electric field. Correcting for this change, the flow of the gravitationally induced current in the presence of the eastward electric field involves the expenditure of electrical energy just sufficient to agree with the increase in potential energy of the plasma as it moves upward in the gravitational field.

When collisions are introduced, they provide a drag on the upward motion of the plasma. If the upward motion is to be maintained in the face of the drag, an energy source is required. This is provided by the flow of Pederson current, a consequence of the same collisions that produce the drag. Energy is drawn from the source of the electric field in the amount required to match the energy dissipated by viscous drag. If the applied field is maintained constant, a change in the viscous drag simply adjusts the Pederson current and the electrical energy drawn from the external source. On the other hand, if the Pederson current is maintained constant, a change in the viscous drag must be accompanied by a change in the eastward field and the associated upward drift velocity.

When the geomagnetic field is not horizontal and the plasma density distribution along the field lines is not hydrostatic, viscous interaction with the neutral atmosphere transfers some of the weight of a hypothetical vertical unit column of plasma to the atmosphere (the fact that the plasma pressure at the apex of a field line is not zero is equivalent to the extension of the hypothetical vertical column from the apex altitude to infinity). The pressure at the apex tends to distend the magnetic field there (probably resisted by adjoining tubes) and adds to the downward thrust on the neutral atmosphere in the viscous region below the ion peak. The component perpendicular to the field lines of the gravitational force on the plasma produces a gravitationally induced current that transfers that component of the weight of the plasma to the magnetic field. Similarly, density gradients perpendicular to the magnetic field in the north-south direction have associated with them magnetization currents that augment or detract from the gravitationally induced current, analogous to the equatorial situation discussed earlier.

Consider an isolated tube of plasma in the gravitational field. By isolated, we mean not connected electrically to the adjoining plasma. Then the gravitationally driven current results in charge accumulation on the east and west boundaries of the tube and a westward electric field, which corresponds to inward drift. The eastward flow of gravitationally induced current in the presence of the westward electric field represents a source of electrical energy at the expense of gravitational energy. The electrical energy appears in part as pure field energy, $\varepsilon_o E^2/2$, but principally as energy stored in the dielectric, $\chi_e \varepsilon_o E^2/2$, with $\chi_e \approx 10^5$, in the form of kinetic energy. What happens in the absence of collisions is that the isolated tube of plasma falls under action of gravity and acquires kinetic energy corresponding to its loss of potential energy in the gravitational field.

When the effect of collisions is introduced, there is drag on the falling tube of plasma that slows its fall. This shows up electrically by the appearance of Pederson conductivity and a westerly Pederson current that tends to cancel the gravitationally induced current and the rate of build up of westward field. The difference between the two currents is profound. The gravitationally induced current flowing against the electric field constitutes a dynamo, and the Pederson current flowing with the electric field constitutes a load that reduces the rate of build up of westward field. The Pederson current is dissipative and represents deposition of heat in the atmosphere; some of the gravitational energy that was being converted into kinetic energy now appears as heat. To prevent tubes of plasma from falling under action of gravity, the environment must be such as to prevent the east-west charge separation from developing. It is possible that such properties of the environment prevent empty tubes below the ionosphere from rising buoyantly through the ionosphere; i.e., they prevent the development of the eastward field that the empty tubes would require to rise.

Magnetic Variations

The stress exerted on the magnetic field by the weight of the ionosphere is small compared to that associated with magnetic variations. The magnetic pressure associated with a 0.3 gauss field is $(3 \times 10^{-5})^2/2 \times 1.26 \times 10^{-6} = 3.6 \times 10^{-4}$ Pascal (1 Pascal = 10 dyne/cm^2 = 10^{-5} bar). A 100 gamma variation in total magnetic field strength changes this pressure by 2.4×10^{-6} Pascal; most quiet day variations are less than this, although the variations below the equatorial electrojet are about 50% larger. By contrast, the weight of the ionosphere per unit area, approximated by a 100-km thick layer with 10^6 ions (mass 30) per cc is 5×10^{-8} Pascal.

In the daytime equatorial region, normal quiet-day (S_q) ionospheric currents compress the magnetic field below the current system and in so doing exert an upwards stress on the ionospheric plasma near 108 km, stress that must be communicated in turn to the neutral atmosphere since it is far in excess of the weight of the ionosphere. The neutral pressure in the vicinity of the current system is about 0.1 Pascal, so the neutral atmosphere is well able to withstand the stress of the magnetic variations. The weight of the ionosphere provides on the order of 1% of the daytime downward stress on the magnetic field. At night, the normal quiet-day ionospheric current is westward, exerting an upward force on the magnetic field. The upward nighttime force on the magnetic field near 108 km is more than an order of magnitude less than the downward daytime force. However, the upward force on the magnetic field near 108 km is greater than the downward force just below the F peak due to the weight of the overlying atmosphere, so the net force on the magnetic field at night is upward. Thus the nighttime current system at low latitudes exerts a downward force on the neutral atmosphere, slightly increasing the atmospheric pressure.

Rocket measurements at the dip equator have indicated a current density 8×10^{-6} A/m^2 at an altitude of 108 km, with a half width 12 km (Kelley p 89), normalized to a 100 nT variation at Huancayo. This corresponds to a current of 10^2 A/km and a $\Delta\mathbf{B}$ across the layer of 125 nT. Depending upon the assumed geometry, this corresponds to a variation in the north component at the dip equator somewhat less than 125 nT. The variation decreases by a factor of about 2 or 3 as the latitude increases by 10°, the factor being largest under equinoctial conditions. The current is described as being driven elsewhere (i.e., from higher latitudes, Ratcliffe p 86); this implies that the electric field in the equatorial region is in the direction of the current flow, i.e., along the magnetic equator. However, wind directed along the equator could also drive currents, including Hall currents, giving rise to currents not related to applied fields. Also, some regions along the equator might serve as generators, with the field opposed to the direction of current flow.

The gravitationally induced current flows eastward, day or night; the nighttime flow is against the normal pattern of electric field and varies from about 0.4 A/km at solar minimum to 1.2 A/km at solar maximum; the daytime flow varies from about 1.2 A/km at solar minimum to 6 A/km at solar maximum. The quiet day global currents, scaled from Chapman's figures, are about 21 A/km during the middle part of the day, about 7 A/km during the evening, and perhaps 4 A/km in the early morning hours. The possibility exists that the net nighttime current may at times be eastward while the field is westward.

The daytime Pederson currents greatly exceed the gravitationally induced current, so the magnetic variation at the earth's surface is mainly due to the flow of Pederson or Cowling currents.

From the Satellite Environment Handbook, it appears that

- The contributions from the E and F regions to the currents responsible for the daytime magnetic variations are about equal at solar maximum, but mainly E region at solar minimum.
- The Pederson currents at night are much smaller than the daytime currents, with possibly equal contributions from the E and F regions at solar minimum but mainly F region at solar maximum.
- Close to the equator, E region Cowling conductivity always dominates.

The magnetization (plasma pressure gradient) current cannot be diverted; it follows the pressure contours of the plasma. Something must happen to the gravitationally induced current when it enters a region of different density, either diversion or change in the electric field (i.e., charge accumulation).

The downwards stress on the magnetic field during the daytime is mainly due to E region current. The F region current also presses downwards on the magnetic field, but in an amount corresponding only to the weight of the ionosphere near and above the F peak. As mentioned above, the total downwards stress is much greater than the weight of the ionosphere and it is associated with an upwards lift on the neutral atmosphere. The pre-reversal peak in upwards drift at Jicamarca is probably due to a decrease in E region conductivity at sunset, thus releasing the stress associated with the E region current.